Transactions, SMiRT-25
Charlotte, NC, USA, August 4-9, 2019
Division IV

UNDERSTANDING THE ASSUMPTIONS IN DESIGN RESPONSE SPECTRA FOR SEISMIC TIME HISTORY ANALYSES

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ABSTRACT

Our recent experience showed that enveloping the design response spectra alone will not prevent power deficiencies in the synthetic acceleration time histories. This finding contradicts a popular belief in recent years that the use of stricter response spectrum enveloping criteria could avoid the need of checking power spectral density functions. Using the results of our targeted analyses, this paper explains why enveloping response spectra alone is not adequate and it is necessary to restore the check of power spectral density functions, as initially suggested by Dr. Robert Kennedy and Prof. Masanobu Shinozuka in the 1980's. More importantly, this paper also reinforces an obvious but often neglected concept that design response spectra, as the common and only practical way of input motion specification, implicitly require an adequate frequency distribution of power in the time histories. This requirement cannot be satisfied without some explicit considerations besides enveloping the design response spectra.

INTRODUCTION

In the 1980's, Kennedy and Shinozuka (NUREG/CR-5347, 1989) and others recognized that the acceptance criteria in the NUREG-0800 Standard Review Plan (SRP) of synthetic time histories enveloping only multiple design response spectra (DRS), were not capable of preventing power deficiencies in the generated time histories. If a power deficient time history is used in the seismic analysis of safety-related structures, systems, and components (SSCs) of nuclear power plants, it could significantly underpredict seismic demands to the SSCs, which could potentially lead to unsatisfactory designs. To resolve this issue, Kennedy and Shinozuka recommended necessary provisions in NUREG/CR-5347 to check the power spectral density (PSD) functions in addition to the DRS enveloping criteria, which were implemented in SRP Section 3.7.1, "Seismic Design Parameters," Revision 2 (1989). About two decades after that monumental work, another approach, which involved enveloping only the 5 percent-damped DRS using more stringent criteria, was introduced in ASCE 4, ASCE 43 and the SRP. Many have believed that this approach can avoid a PSD check because it compares the calculated response spectrum (RS) to the DRS at a denser list of frequency points and uses an upper bound check at 130 percent of the DRS. This paper aims to provide a technical rationale about the inadequacy of this approach.

In the current practice, structural engineers use input response spectra (IRS) obtained from seismic hazard analyses to perform seismic response analyses and design of safety-related NPP SSCs. Subsequently, in-structure response spectra (ISRS) from structural response analyses are used by

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mechanical engineers to analyze and qualify the equipment. Besides IRS or ISRS, rarely has there been a practical need for seismologists to provide anything else to structural engineers or for structural engineers to pass on anything else to mechanical engineers. In fact, as practiced through many codes and standards such as the SRP, ASCE 4, and ASCE 43, DRS, an alternate term for IRS used in this paper to reflect the fact that not all design response spectra are developed from a seismic hazard analysis, have been used to describe and specify the input ground motions.

However, response spectra are not a direct representation of the underlying ground motions. For a given spectral frequency, a response spectrum describes the maximum response of a single degree-of-freedom (SDOF) oscillator subjected to a given input time history at a given damping ratio, typically 5% in probabilistic seismic hazard analyses. Therefore, a response spectrum by itself does not provide a precise description of the frequency content in the underlying time history and in its strong motion duration. More specifically, the frequency content represented by the response spectrum as a function of the oscillator frequency does not always adequately reflect the frequency content represented by the Fourier amplitude spectrum or equivalently the power spectral density function of the ground motion. Our experience has shown that in analyses where synthetic time histories are generated to envelop the DRS, assumptions made about the ground motions can significantly affect the calculated ISRS and potentially other structural responses as well. This experience has led to several questions, such as other types of information required beyond the DRS itself to fulfil its role of interfacing between seismologists and engineers; assumptions made on one side of this interface being equally applied on the other side; the potential consequences of differing assumptions and the additional information needed to address these potential differences and consequences.

This paper attempts to address some of these questions, with the goal of establishing a more coherent understanding of the design ground motions and the related DRS, and to help ensure consistent and robust generation of synthetic ground motion time histories for design purposes. The paper also provides an assessment of the widely applied acceptance criteria for synthetic acceleration time histories and discusses how these criteria should be enhanced. The goal of such an enhancement is to ensure that the assumptions used to develop the DRS are accounted for and evaluated in the development of the synthetic time histories, so that they can appropriately represent the underlying ground motions in the seismic analyses for the design of SSCs.

A BRIEF HISTORY OF ACCEPTANCE CRITERIA FOR ACCELERATION TIME HISTORIES

The acceptance criteria for RS enveloping in common codes and standards, such as ASCE 4 and ASCE 43, are not much different from the SRP guidance. Using the SRP as an example, a brief history is provided below to show the progress of these criteria. SRP Section 3.7.1 has been revised four times to accommodate various enhancements and additions since its first release in 1975. The amount of information has greatly expanded, partly because of technological advances in seismic analyses and vastly improved access to highly capable computational power. Relevant to the topic of this paper, a significant portion of this information expansion in the SRP is devoted to the acceptance criteria for design input motions, i.e., DRS and design time histories (DTH), signifying their importance as the upstream parameters in the whole process of seismic analysis and design.

In the initial release of SRP Section 3.7.1 (NUREG-0800, 1975), "Seismic Input", which is now "Seismic Design Parameters," the acceptance criteria for DRS enveloping require both a comparison of spectral values at all specified damping values and a review of frequency intervals at which the RS values are calculated from DTH. The frequency intervals must be small enough such that any reduction in these intervals does not result in more than a 10 percent change in the computed RS. Table 3.7.1-1 of SRP Section 3.7.1, which all revisions have retained without any change, lists a series of acceptable frequencies. This revision also indicates that an acceptable alternative method is to choose a set of frequencies such that each frequency is within 10 percent of the previous one. As for acceptance criteria for RS enveloping, the initial release states that no more than five points of the RS estimated from the time history should fall below the DRS and that no point should fall below the DRS by more than 10 percent.

SRP Section 3.7.1, Revision 1 (NUREG-0800, 1981) did not deviate from the initial release with regard to the criteria for RS enveloping. SRP Section 3.7.1, Revision 2 (NUREG-0800, 1989) was strongly influenced by NUREG/CP-0054 (1986), NUREG/CR-5347 (1989), and NUREG/CR-3509 (1988). This revision provides criteria on the total duration (10 to 25 seconds) and the strong motion duration (6 to 15 seconds) of the time histories for linear analyses. Implementing the work by Kennedy and Shinozuka, as documented in NUREG/CR-5347, this revision states that a target PSD function criterion must be satisfied in addition to the DRS enveloping criteria. It recognized that for the time histories enveloping the same DRS, their PSD functions can fluctuate significantly and randomly as a function of frequency. It also recognized that the more closely the time histories match the DRS, the more significantly and randomly the PSD functions fluctuate. More importantly, these fluctuations may lead to an unconservative estimate of the responses of some SSCs. Appendix A to SRP Section 3.7.1 provides the target PSD function compatible with the DRS in Regulatory Guide (RG) 1.60 (2014), “Design Response Spectra for Seismic Design of Nuclear Power Plants.”

SRP Section 3.7.1, Revision 3 (NUREG-0800, 2007) maintained the Revision 2 RS enveloping criteria as Approach 1 and introduced a new approach called Approach 2 based on NUREG/CR-6728 (2001). For Approach 1, the frequency interval criterion was simplified to use only the acceptable frequencies in Table 3.7.1-1. As for PSD check, the new Appendix B included guidelines and procedures for DRS other than RG 1.60 DRS. Approach 2 provided provisions for the time histories to envelop only the 5 percent damped RS but required the RS be computed and compared at much denser frequency points than those required for Approach 1. The computed RS should not fall more than 10 percent below the DRS at any frequency and should not fall below DRS in any consecutive frequency window larger than ±10 percent of any frequency. In addition, Approach 2 also stated that the computed RS should be below 130 percent of the DRS in lieu of the PSD criterion of Approach 1.

SRP Section 3.7.1, Revision 4 (the current revision, NUREG-0800, 2014), includes enhancements about PSD check and target PSD functions (Nie, et al., 2015; Xu, et al., 2014). Appendix B was significantly revised to introduce a new procedure to generate the target PSD function for any practical DRS other than RG 1.60 DRS. Approach 2 was enhanced by making the PSD assessment non-optional. It states that the PSD function should be computed and shown to have no significant gaps in power over the frequency range of interest; however, it does not explicitly necessitate a comparison to a target PSD function.

The current ASCE 4 and ASCE 43 procedures are close to Approach 2 in SRP Revision 3. In summary, the SRP Approach 2 and the ASCE 4 and ASCE 43 procedures became the most widely used acceptance criteria for synthetic acceleration time histories, particularly because unlike Approach 1, these criteria do not require a comparison of the computed PSD function to a target PSD function. The rest of the paper will show why a check of the PSD function against a target PSD function, is still applicable to these criteria.

WHY MATCHING DRS ALONE IS NOT SUFFICIENT

Representing the ground motions, DRS can be used in response spectrum analysis (RSA) to estimate the maximum structural responses. For certain structural responses such as ISRS, time history analyses are often employed using synthetic acceleration time histories generated from DRS. At a high level, time histories can be considered as surrogates for the DRS in transferring the ground motions as a structural demand to the SSCs. However, because many time histories can be developed to represent the same DRS, some time histories may have "features" or "defects" that can lead to significantly underestimated structural responses, as opposed to the common impression that time history analyses are a more rigorous approach. These features or defects are often very difficult to detect.

In addition to establishing the need and details about the PSD check, NUREG/CR-5347 also envisioned that an appropriate set of RS enveloping criteria might be able to conveniently prevent power deficiency in time histories. Along the same line, the approach proposed in NUREG/CR-6728 and adopted in ASCE/SEI 43-05, ASCE 4-16, and the SRP Section 3.7.1 guidance (since Revision 3) includes numerical criteria that require the estimated RS to be between 90 and 130 percent DRS to ensure power sufficiency in the time histories. However, our experience indicates that, in some cases, acceleration time histories developed using these criteria can still have large power deficiencies in some frequency ranges. Moreover, a recent study by Houston et al. (2010) used hundreds of synthetic time histories and showed that meeting those criteria cannot prevent some time histories from having power deficiencies in large frequency windows. This study especially concluded that the power deficiencies could lead to an unconservative estimate of ISRS by as much as 70 percent. These experiences help raise the question of why these RS enveloping criteria are not adequate to ensure power sufficiency in the generated time histories and thus could underestimate the ISRS.

By definition, the only assurance RS-based criteria can provide is how close to the DRS the maximum responses of the single-degree-of-freedom oscillators are at their fundamental frequencies. They can neither provide any restrictions on the time when a maximum response occurs along the time history (e.g., a maximum response can occur inside or outside of the strong motion duration) nor prescribe what frequency components in the time history contribute the most to the maximum response of an oscillator with a given frequency. Following these two lines of reasoning, examples given below show conditions in which RS enveloping criteria are satisfied but the generated time histories clearly would not be acceptable in practice.

For the first line of reasoning, a time history can be constructed by concatenating many segments of miniature time histories, each of which is a sinusoid at a single frequency. Each miniature time history creates the maximum response of a particular oscillator in the series of oscillators in generating the RS. These miniature time histories may be separated in the final time history by zero padding so that the responses to these individual miniature time histories do not combine with each other. This time history can match the DRS exactly because each sinusoid can be scaled linearly and independently so that its maximum response equals the DRS at the frequency of this sinusoid. This is a much stricter match than the range of 90 to 130 percent DRS currently specified. Certainly, this type of time histories is not acceptable in practice. However, without using other means to prevent the maximum responses from occurring anywhere in the time history, a time history constructed in this manner can perfectly meet the RS enveloping criteria to the strictest level. Although concatenating miniature time histories cannot create a realistic time history, it exemplifies a typical problem of *frequency nonstationarity* by which two or more bands of frequency components do not occur in the same time interval in the time history. The problem with frequency nonstationarity is that the structural responses to these frequency bands are not combined and the total responses may be underpredicted. Plotting time histories often does not detect the problem of frequency nonstationarity as the clouds of many data points are not much different from time history to time history. A PSD check can conveniently identify the issue of frequency nonstationarity in a time history; however, this paper does not have space for a detailed discussion on this topic.

For the second line of reasoning, the RS enveloping criteria cannot guarantee the correlation between the spectral frequency at which an oscillator reaches its maximum response, and the major frequencies in the time history that contribute to the maximum response of the oscillator at this spectral frequency. This correlation is important for a time history as a surrogate to represent appropriately the DRS in seismic analysis; otherwise, the results of the RSA method can be significantly different from those of the time history analysis method. The lack of such correlation would fail the role of the time history as a surrogate for the DRS. (The example above consisting of miniature time histories is another type of unacceptable representation of the DRS.) The next example is to demonstrate the problem in which one or more frequency bands mask other frequencies in the RS enveloping process so that the resultant time history is deficient in power at those frequencies being masked.

In this example, 15 sinusoids were combined and then used as the seed record to generate a synthetic acceleration time history. These sinusoids were assumed to have random phases, and their frequencies were spaced linearly between 0.3 Hz and 24 Hz on the log scale. The amplitudes of these 15 sinusoids were initially selected so that a linear combination of their RS would fit best to the RG 1.60 horizontal DRS. Using the typical RS enveloping criteria described in this paper, some iterations and manipulations were performed on this seed to envelop the DRS. In this process, some low amplitude components at other frequencies were introduced inevitably by procedures, such as baseline correction, application of an intensity function, high pass filtering, and fractional folding. Figure 1 shows that the resultant acceleration time history meets the RS enveloping criteria from 0.1 Hz to 100 Hz.

The major frequencies in the time history can be identified through its Fourier spectrum or the PSD function. Figure 2 shows the PSD check of this acceleration time history in which the strong motion duration was selected as 7.175 seconds based on the Husid plot. This duration corresponds to a 5% to 75% increase in Arias Intensity. A longer strong motion duration up to about 10 seconds would not change much the estimated PSD function. The target PSD function is taken from SRP Section 3.7.1, Appendix A. The minimum target PSD function is 80 percent of the Appendix A target PSD function. The PSD check clearly shows that the raw PSD function is generally and significantly lower than the minimum target PSD function, indicating severe power deficiencies at many frequencies. Using a ±5 percent frequency window to smooth the raw PSD function produces a mean curve representing well the general trend of the raw PSD curve. Had a ±20 percent frequency window been used, the mean PSD curve would be much higher and would incorrectly indicate a much less power deficiency. The ±5 percent frequency window for PSD smoothing in this example is comparable to the width of the half power window for the amplification function of a 5 percent damped oscillator. This observation may suggest that the frequency window for PSD smoothing should be consistent with the damping ratio used in the RS enveloping process in order to identify a potential power deficiency relevant to the characteristics of the oscillator.

These examples clearly show that the RS enveloping criteria alone are not sufficient to ensure power sufficiency and that RS enveloping criteria must be used in conjunction with a PSD check against the minimum target PSD function to determine whether the distribution of power is adequate over the frequency of interest. A PSD check can also identify the issue of frequency nonstationarity because frequency components that occur outside of the strong motion duration or occur in a period shorter than the strong motion duration would lead to a lower PSD estimate at those frequencies.

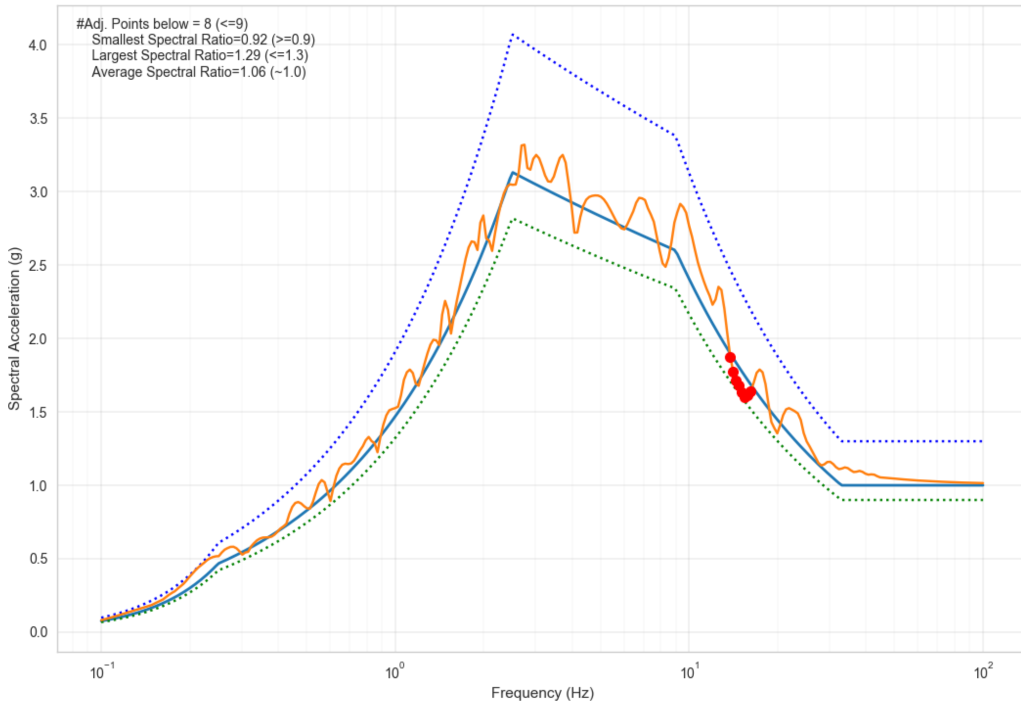

Figure 1 Accelerogram with 15 major frequencies that meet the RS enveloping criteria

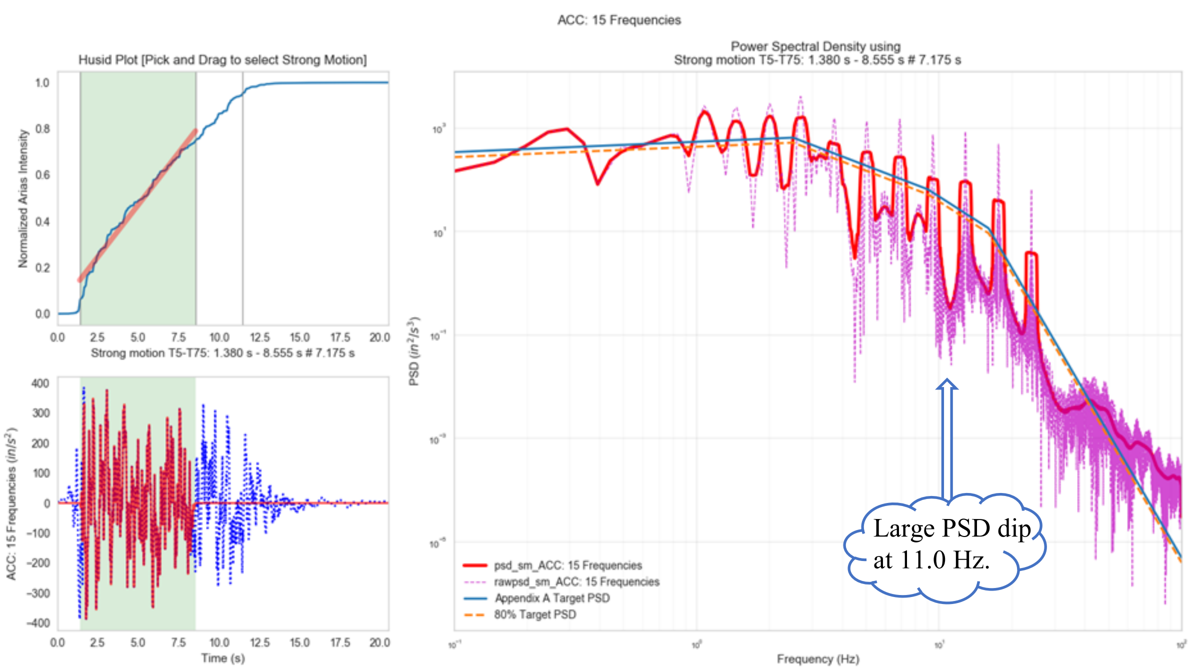

Figure 2 PSD check of the accelerogram with 15 major frequencies (±5-percent window)

EFFECTS OF MATCHING DRS BUT DEFICIENT IN POWER

The recent study by Houston et al. (2010) found that some of the hundreds of time histories used in that study, all having met the RS enveloping criteria, lead to an underprediction of ISRS by as much as 70 percent at some frequencies. This conclusion was based on the coefficient of variance in the predicted ISRS. We present below a comparison of the ISRS of the same SDOF structure subjected separately to two acceleration time histories: the one with mainly 15 frequencies described above (designated as TH A) and one broadband time history (designated as TH B), both satisfying the same RS enveloping criteria. Figure 3 compares the RS of the broadband time history to the DRS and its 90 percent and 130 percent bounds. The broadband acceleration time history was developed also to meet the secondary PSD check, as shown in Figure 4. The minor dips in the PSD function below the minimum target PSD function are not considered to be significant for this demonstration, because these dips are not in the range of frequencies around 10 Hz that are to be used below in this example. In practice, these dips can be removed by slightly increasing the Fourier amplitudes at those affected frequencies.

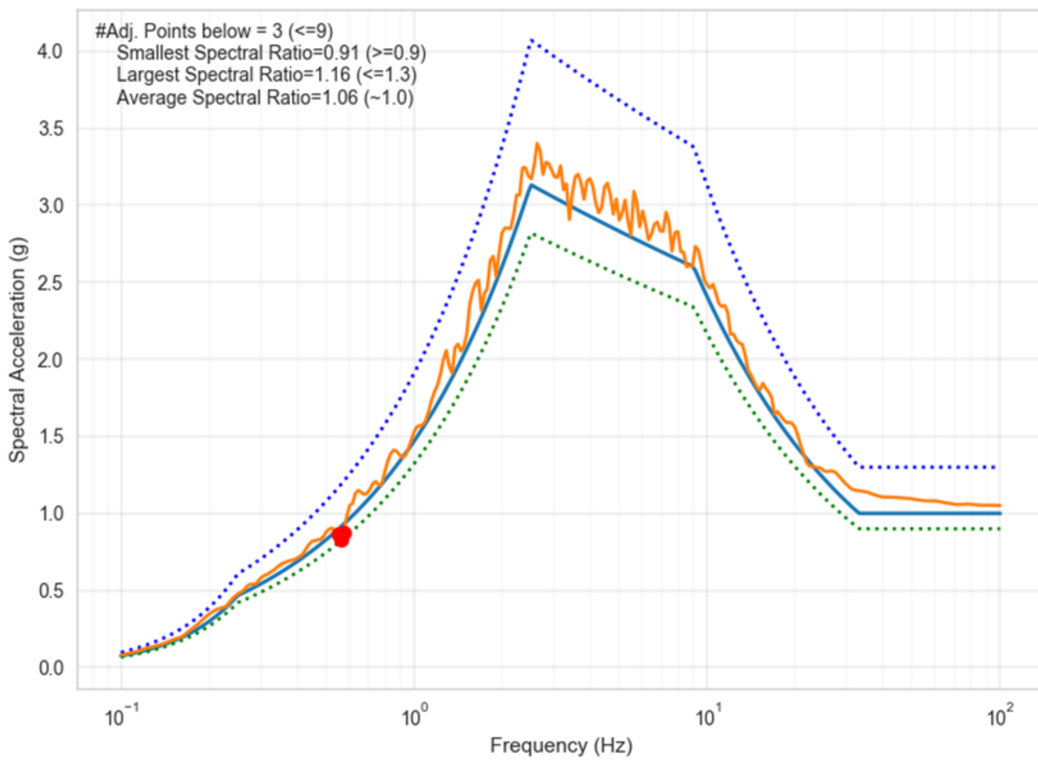

Figure 3 A broadband accelerogram enveloping DRS (piecewise smooth curves showing the criteria)

The SDOF structure was chosen to have a damping ratio of 5 percent and a fundamental frequency of 11.0 Hz, at which a large valley exists in the PSD function of TH A, as shown in Figure 2. The two major frequencies in TH A around 11.0 Hz are 9.5 Hz and 12.9 Hz. As shown in Figure 5, the time history responses of the SDOF structure due to TH A and TH B are obviously different, with the latter having significantly richer frequencies. This observation is consistent with the comparison of their 5% damped ISRS also shown in that figure. The peak ISRS from TH A is only about half of that from TH B. Effectively, the deficient power around 11.0 Hz in TH A is authentically transferred to the ISRS. It should be noted that despite the large differences in the PSD functions and in the ISRS shapes around this frequency, the ZPAs in the ISRS are very similar and close to the DRS at 11.0 Hz. This confirms that the only assurance that the RS enveloping criteria can provide is the maximum response of the oscillator, which corresponds to the ZPA in the ISRS. The RS enveloping criteria do not provide an adequate assurance about the power distribution in the input motion and consequently also the power distribution of the structural response. It should be emphasized that even for an SSC with the same damping ratio as used in the RS enveloping process, the variation of ISRS resulting from different input time histories can still be significantly large. This can even occur at frequencies where the input motions envelop the DRS with a similar level of conservativeness (i.e., the RS of the two input motions are very close at 11.0 Hz). Therefore, this comparison clearly demonstrates that RS enveloping criteria alone cannot ensure that the generated acceleration time history is adequate. On the other hand, a PSD check by comparing against a target PSD function can clearly identify power deficiencies.

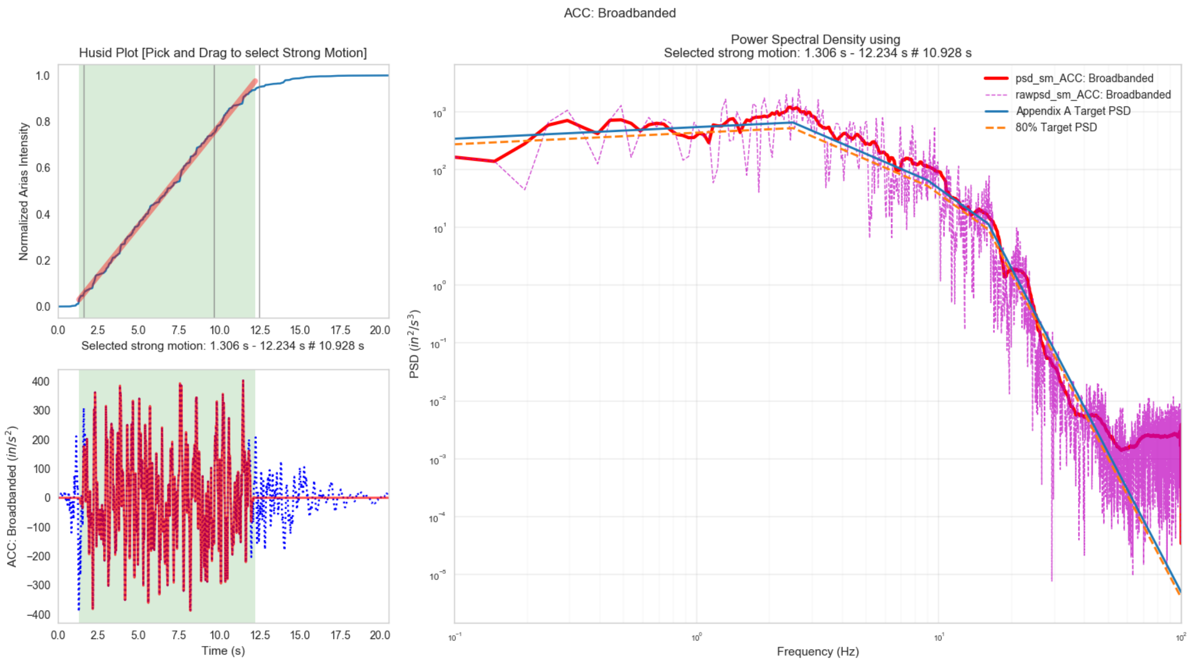

Figure 4 A PSD check of the broadband accelerogram (±20 percent window)

CONCLUSIONS

This paper shows that RS enveloping criteria alone cannot ensure power sufficiency in the generated time history, and an explicit assessment of the PSD function against a target PSD function can identify any power deficiency. This finding is consistent with the early views established by Kennedy and Shinozuka in NUREG/CR-4357. In addition, a PSD assessment without a comparison to a target PSD function is not conclusive because without a target, visual inspection of a PSD function cannot identify a broad power deficiency over a large frequency range, which does not manifest itself as a clear valley. This paper also demonstrates that a power deficient time history can significantly underpredict the ISRS and potentially also any frequency dependent structural responses.

More importantly, without recognizing that DRS implicitly carry an assumption that the underlying ground motions represented by DRS should have a broadband power distribution, the RS enveloping criteria can be satisfied by narrow-banded synthetic acceleration time histories. For the time history analysis method to be an adequate tool in estimating the seismic demands to SSCs, the synthetic time histories should be treated as part of that tool. Frequency stationarity should also be an assumed requirement on the time histories; otherwise, structural responses at different modal frequencies would not have enough opportunities to combine and consequently the estimated structural response could be unconservative. In general, seismologists have developed the IRS (DRS in a generic sense) by condensing many parameters in the field of seismology and geophysics. Accordingly, the application of this simplistic form of DRS by structural engineers should effectively unpack those key seismological parameters. Without a careful consideration of those parameters, DRS can be overly simplistic and may not serve well its role as the interface between seismologists and structural engineers. This paper certainly has not covered many of those parameters (for example, target PSD functions compatible with DRS and strong motion durations). However, we hope that this paper has identified a need to renew the traditional dialogue between these two technical specialties, because without that, the seismic hazards characterized by seismologists are not necessarily the same as mitigated by structural engineers.

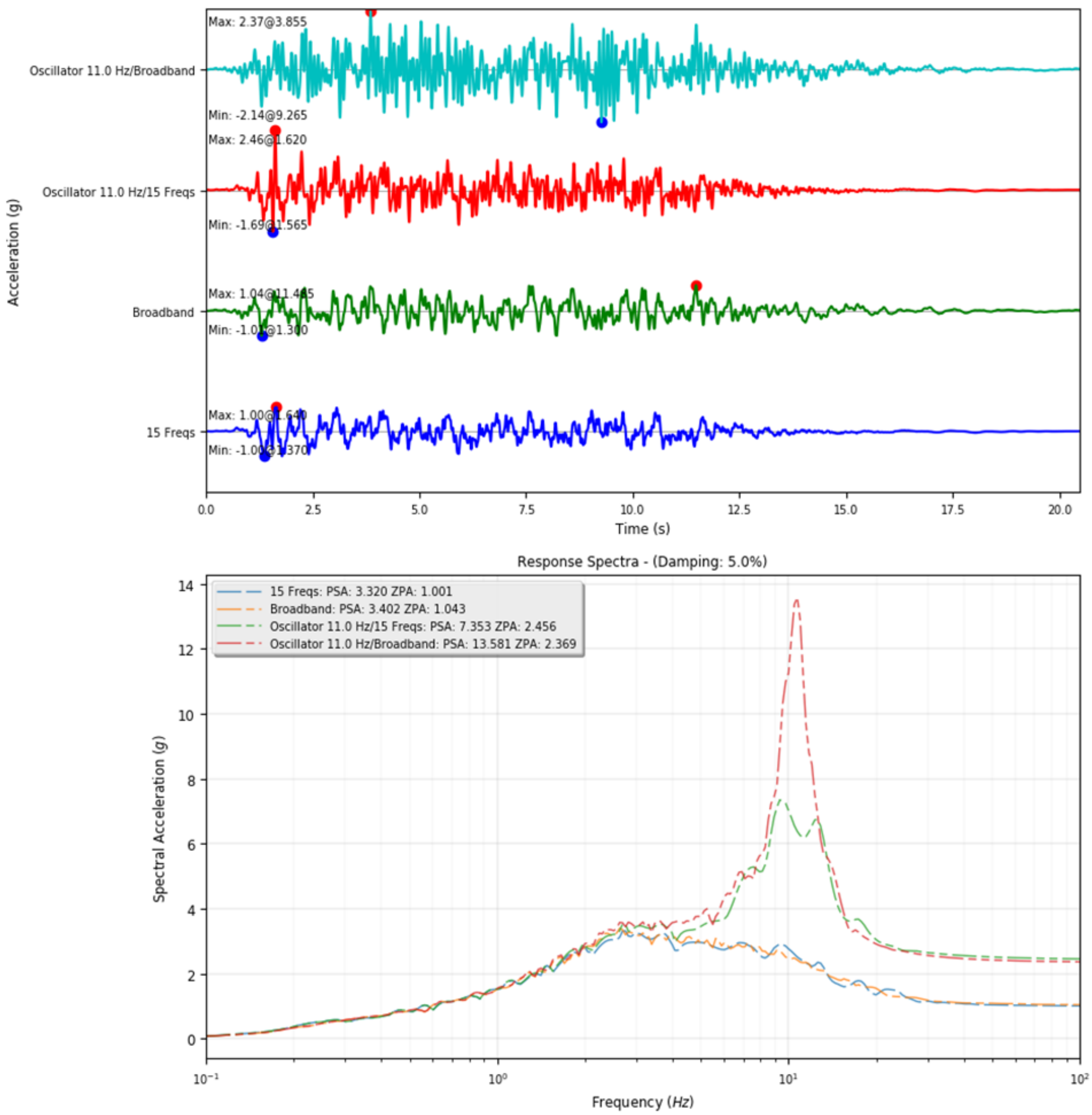

Figure 5 Absolute responses of the 11.0 Hz SDOF structure with a 5 percent damping ratio

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